# Polarized Microwave Emission from Dust

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**Abstract.** Polarized emission from dust is an important foreground that can hinder the progress in polarized CMB studies unless carefully accounted for. We discuss potential difficulties associated with the dust foreground, namely, the existence of different grain populations with very different emission/polarization properties and variations of the polarization yield with grain temperature. In this context we appeal for systematic studies of polarized dust emission as the means of dealing with this foreground.

## INTRODUCTION

Diffuse Galactic microwave emission carries important information on the fundamental properties of interstellar medium, but it also interferes with the Cosmic Microwave Background (CMB) experiments (see Bouchet et al. 1999, Tegmark et al. 2000). Polarization of the CMB provides information about the Universe that is not contained in the temperature data. In particular, it offers a unique way to trace specifically the primordial perturbations of tensorial nature (*i.e.* cosmological gravitational waves, see Seljak & Zaldarriaga 1997, Kamionkowski et al. 1997), and allows to break some important degeneracies that remain in the measurement of cosmological parameters with intensity alone (Zaldarriaga et al. 1997, Davis & Wilkinson 1999, Lesgourgues et al. 1999, Prunet et al. 2000). Therefore, a number of groups around the world (see Table 1 in Staggs et al. 1999) work hard to measure the CMB polarization. In view of this work, the issue of determining the degree of Galactic foreground polarization becomes vital.

Among different sources of polarized foregrounds, interstellar dust is probably the most difficult to deal with. We can identify several reason for that. First of all, dust has both a population of tiny grains (Leger & Puget 1984), which are frequently called PAH, along with the "classical" power-law distribution of larger grains (Mathis, Rumpl & Nordsieck 1977). Then the composition of grains changes with their size, which influences both grain temperature and degree of grain alignment. Moreover, both recent experience with microwave emissivity and theoretical studies of expected polarization response (Draine & Lazarian 1999) show that the naive extrapolation of the grain properties from FIR to microwave does not work. If we take into account that the very nature of dust alignment that causes the polarization still remains somewhat mysterious after more than half a century after its observational discovery (see review by Lazarian 2000), the scope of the problem becomes apparent.

The discovery of the anomalous emission in the range of 10-100 GHz illustrates well the treacherous nature of dust. Until very recently it has been thought that there are three major components of the diffuse Galactic foreground: synchrotron emission, free-free radiation from plasma (thermal bremsstrahlung) and thermal emission from dust. In the microwave range of 10-90 GHz the latter is subdominant, leaving essentially two components. However, it is exactly in this range that an anomalous emission was reported (Kogut et al. 1996a, 1996b). In the paper by de Oliveira-Costa et al. (2000) this emission was nicknamed "Foreground X", which properly reflects its mysterious nature. This component is spatially correlated with 100 $\mu$m thermal dust emission, but its intensity is much higher than one can expect by directly extrapolating thermal dust emission spectrum to the microwave range. It is very likely that discoveries of such a nature are expected when the foreground polarimetry is performed.

In this review, we briefly summarize what is known about the grain populations, grain emission and grain alignment. We discuss the origin of the Foreground X and its expected polarization. Earlier reviews of the subject include (Prunet & Lazarian 1999, Draine & Lazarian 1999 and Lazarian 2000).

## OBSERVATIONAL EVIDENCE

### Infrared emission: extrapolation to microwave range

Emission spectrum of diffuse interstellar dust was mostly obtained by *InfraRed Astronomy Satellite* (IRAS) and infrared spectrometers on the *COsmic Background Explorer* (COBE) and on the *InfraRed Telescope in Space* (IRTS).

The emission at short wavelength, e.g. $< 50\ \mu$m, arises from transiently heated very small grains. These grains have so small heat capacity that the absorption of a single 6 eV starlight photon rises their temperature to $T > 200K$. Typically these grains have less than 300 atoms and can be viewed as large molecules rather than dust particles. They are, however, sufficiently numerous to account for $\sim 35\%$ of the total starlight absorption. The contribution of those grains at the microwave frequencies was thought to be negligible.

In terms of CMB studies the most important is the emission from cool classical dust. Far infrared emission in the range from 1 mm (300 GHz) to 100 $\mu$m (3000 GHz) is primarily due to dust particles heated by starlight to temperatures around 20 K. Those particles are "classical" grains known from ground-based starlight absorption studies. It is convenient to approximate the far infrared emission with $\nu j_\nu$ peaking at $\lambda_m \sim 130\ \mu$m and following the power-law corresponding the absorption cross section $\sim \nu^\beta$, where $\beta \sim 1.7$, and temperature $T_{dust} = \frac{hc}{\lambda_m k(4+\beta)}$ (see discussion in Draine & Lazarian 1999). It was considered natural to extrapolate this fit to frequencies lower than 300 GHz, and no other contribution was expected from large dust particles.

If the extrapolation from infrared to microwave were as simple as it is suggested above, dealing with dust contribution would be trivial. Further research, however, revealed a much more complex picture. Both classical and small grains were shown to be more important microwave emitters than researchers used to assume. For tiny grains a new mechanism of emission was found (Draine & Lazarian, 1998,a, henceforth DL98a, Draine & Lazarian 1998b, henceforth DL98b), while magnetic properties were shown to be important for microwave emissivity of large grains (Draine & Lazarian 1999). This example should be used to caution against simple minded attempts to extrapolate polarization from infrared to microwave range.

### Anomalous microwave emission: unexpected discovery

Until very recently it has been thought that there are three major components of the diffuse Galactic foreground: synchrotron emission, free-free radiation from plasma (thermal bremsstrahlung) and thermal emission from dust. In the microwave range of 10-90 GHz the latter is definitely subdominant, leaving essentially two components. However, it is exactly in this range that an anomalous emission was reported (Kogut et al. 1996a, 1996b). In the paper by de Oliveira-Costa et al. (2000) this emission was nicknamed "Foreground X", which properly reflects its mysterious nature. This component is spatially correlated with 100 $\mu$m thermal dust emission, but its intensity is much higher than one can expect by directly extrapolating thermal dust emission spectrum to the microwave range.

Since its discovery the Foreground X has been detected in the data sets from Saskatoon (de Oliveira-Costa et al. 1997), OVRO (Leitch et al. 1997), the 19 GHz survey (de Oliveira-Costa et al. 1998), and Tenerife (de Oliveira-Costa et al. 1999, Mukherjee et al. 2000). Initially, the anomalous emission was identified as thermal bremsstrahlung from ionized gas correlated with dust (Kogut et al. 1996a) and presumably produced by photoionized cloud rims (McCullough et al. 1999). This idea was subjected to scrutiny in Draine & Lazarian (1997) and criticized on energetic grounds. Additional arguments against the free-free hypothesis became available through correlating anomalous emission with ROSAT X-ray C Band (Finkbeiner & Schlegel 1999) and H$\alpha$ with 100 $\mu$m emission (McCullough et al. 1999). They are summarized in Draine & Lazarian (1999). Recently de Oliveira-Costa et al. (2000) used Wisconsin H-Alpha Mapper (WHAM) survey data and established that the free-free emission "is about an order of magnitude below Foreground X over the entire range of frequencies and latitudes where is detected". The authors conclude that the Foreground X cannot be explained as free-free emission. Additional evidence supporting this conclusion have come from a study at 5, 8 and 10 GHz by Finkbeiner, Schlegel , Frank & Heiles (2001).

The spectrum of the Foreground X is not consistent with synchrotron emission, and maps at 408 MHz (Haslam 1981) and 1.42 GHz (Reich & Reich 1988) do not correlate with the observed 15-100 GHz intensity, so the anomalous emission is evidently not synchrotron radiation from relativistic electrons.

Correlations of the Foreground X with dust induced Draine & Lazarian (1998a,b, 1999) to conjecture that it can be indeed due to dust. It is encouraging that the observational evidence obtained since the theoretical predictions were published has supported the theory.

## Polarization from dust: half a century puzzle

Polarization due to interstellar dust alignment was discovered in the middle of the last century (Hiltner 1949, Hall 1949) and was studied initially via starlight extinction and more recently through emission. Correlation of the polarization with the interstellar magnetic field revealed that electric vector of light polarized via starlight extinction tend to be parallel to magnetic field[1]. This corresponds to grains being aligned with their longer axes perpendicular to the local magnetic field. Due to the presence of the stochastic magnetic field, the polarization patterns are pretty involved.

The existing data presents a complex picture. It is generally accepted that the observations indicate that the ability to produce polarized light depends on grain size and grain composition. For instance, a limited UV polarimetry dataset available indicates that graphite grains tend not to be aligned (see Clayton et al. 1997), while maximum entropy technique applied to the existing data by Martin & Kim (1995) show that large $> 6 \times 10^{-6}$ cm grains are responsible for the polarization via extinction.

Moreover, the environment of grains seems to matter a lot (Goodman 1995, Lazarian, Goodman & Myers 1997). A study by Arce et al. (1998) indicates that grains selectively extinct starlight up to optical depth $A_v < 3$. Recent emission studies (Hildebrand et al. 1999, 2001) produced a polarization spectrum for dense clouds that reveal a tight correlation between grain temperature and its ability to emit polarized light. As multicomponent fits invoking grains of different temperature were claimed to provide a better fit for the observed 1 mm-100 $\mu$m emission (see Finkbeiner, Schlegel & Davis 1999), this correlation may be very troublesome for the attempts to construct polarization templates.

# POLARIZED EMISSION FROM CLASSICAL DUST

## Grain alignment: light at the end of the tunnel?

The basic explanation of polarized radiation from dust is straightforward. Aligned dust particles preferentially extinct (i.e. absorb and scatter) the $E$-component of starlight parallel to their longer axis. Thermal $E$-component of the emitted radiation, on the contrary, is higher along the longer axis. Thus for aligned grains one must have polarization. What is the cause of alignment?

Grain alignment is an exciting and very rich area of reseach. For example, two new solid state effects have been discovered recently in the process of understanding grain dynamics (Lazarian & Draine 1999, 2000). It is known that a number of mechanisms can provide grain alignment (see review by Lazarian 2000 and Table 1 in Lazarian, Goodman, & Myers 1997). Some of them rely on paramagnetic dissipation of rotational energy (Davis-Greenstein 1951, Purcell 1979, Mathis 1986, Lazarian & Draine 1997, Lazarian 1997a, Roberge & Lazarian 1999) , some appeal to the anisotropic gaseous bombardment when a grain moves supersonically through the ambient gas (Gold 1951, Purcell & Spitzer 1971, Dolginov & Mytrophanov 1976, Lazarian 1994, 1997b, Roberge, Hanany & Messinger 1995, Lazarian & Efroimsky 1996). Grains are definitely paramagnetic and sometimes even strongly magnetic. Supersonic grain motions may be due to outflows (Purcell 1969), Alfvenic turbulence (Lazarian 1994) or ambipolar diffusion (Roberge & Hanany 1990).

At present, grain alignment via radiative torques (Draine & Weingartner 1996, 1997) looks preferable, although the theory and the understanding of the mechanism are far from being complete. The mechanism appeals to a spin-up of a grain as it differentially scatters left and right polarized photons ( Dolginov 1972, Dolginov & Mytrophanov 1976). This process acts efficiently if the irregular grain has its size comparable with the photon wavelength. The mechanism can account for the systematic variations of the alignment efficiency with extinction.

However, other mechanisms should also work. For instance, paramagnetic mechanism may preferentially act on small grains (Lazarian & Martin 2002), while mechanical alignment may act in the regions of outflows (Rao et al. 1998). In general, the variety of Astrophysical conditions allows various mechanisms to have their niche.

Note, that in interstellar circumstances grain alignment happens in respect to magnetic field, even if the mechanism of alignment is not of magnetic nature. This is due to the fact that the Larmor precession of grains is so fast compared to the time scales over which either magnetic field changes its direction or the alignment mechanism acts. In general, the alignment may happen both parallel and perpendicular to magnetic field. In most cases, the alignment happens

[1] The polarizations in emission and in extinction are orthogonal if they are produced by the same grains.

with long grain axes perpendicular to magnetic field, however.

The history of grain alignment research is full of surprises. Initially it looked so ubiquitous that observers were not even interested in the theory of alignment. But then it showed that it may fail within molecular clouds. What will be the next surprise?

## Diffuse gas and molecular clouds: different beasts?

Alignment of grains is different in diffuse gas and molecular clouds. Lazarian, Myers & Goodman (1997) showed that in dark clouds without star formation all alignment mechanisms fail. Indeed, grain alignment depends on non-equilibrium processes[2], while interiors of dark clouds are close to thermodynamic equilibrium.

As soon as stars are born within clouds, the conditions in their vicinity become favorable for grain alignment. This explains why far infrared polarimetry detects aligned grains, while near infrared and optical polarimetry fails. The latter point is a subject of controversy. In the recent paper by Padoan et al (2001) it is claimed that far infrared polarimetry does not provide us with any new information compared with optical and near-infrared studies. We are worried about this conclusion. Indeed, if anything, radiative torques must be active near the newly born stars and the spectropolarimetric studies of Hildebrand et al. (2001) indicate the existence of aligned hot grains. These aligned grains are selectively warmer and should reveal the structure of magnetic field in the star cruddle after the star is born. This information is unlikely to be obtained via short-wave polarimetry. Results by Padoan et al. (2001) may be relevant, however, to 850 $\mu$m polarization observed by Ward-Thompson et al. (2000) from dense pre-stellar cores where radiative torques must be inefficient[3].

We may hope that grain alignment in diffuse clouds is more uniform. Radiation freely penetrates them and therefore the radiative torques must ensure good alignment. This assumption was used in Fosalba et al (2002) who related the polarization from dust extinction and the polarization from dust emission. Further research in this direction is necessary.

## Complications: turbulence, heating ...

Interstellar medium is very complex and this tells on polarization. As we have discussed earlier, grain alignment traces the direction of the local magnetic field. In the presence of turbulence, this field is very complex. The resulting polarization depends on the telescope resolution at a particular wavelength. A possible way of dealing with this complication is to correct for the field stochasticity. Tensor description of turbulent magnetic field was obtained in Cho, Lazarian & Vishniac (2002) and this can be used for the purpose.

Earlier on we mentioned that radiative torques may be responsible for the bulk of grain alignment. As starlight also heats the grains the systematic variations in the alignment efficiency are expected for grains of different temperatures. Moreover, radiative torques depend on grain size and grain composition and so do grain temperatures. These and related issues require a further study and a further work on the radiative torque theory is necessary.

It is unfortunate for the CMB research that we still do not understand many processes related to the polarization arising from classical grains. The good news, however, is that we will have to understand those processes along with the structure of Galactic magnetic field at high latitude if we ever want to understand the CMB polarization well. As the bonus from this research we will get an insight into the operation of Galactic dynamo, high latitude MHD turbulence, turbulent mixing and will make many yet unforeseen discoveries.

# POLARIZED EMISSION FROM SPINNING DUST

Can the ultrasmall grains observed via Mid-IR be important at the microwave range? The naive answer to this question is no, as the total mass in those grains is small.

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[2] To avoid confusion we should remind the reader that interstellar grain alignment is very different from the alignment of ferromagnetic particles in the external magnetic field. The latter is the equilibrium process with the align particles corresponding to the lowest energy level of the system. The grain alignment is a *dissipative* process that requires constant driving and vanishes in thermodynamic equilibrium.

[3] Alternatives are discussed in Lazarian (2000).

However, DL98a appealed to a different mechanism of emission, namely, to the rotational emission[4] that must emerge when a grain with a dipole moment $\mu$ rotates with angular velocity $\omega$.

For the model with the most likely set of parameters, DL98a obtained a reasonable fit with observations available at that time. It is extremely important that new data points obtained later (de Oliveira-Costa et al. 1998, de Oliveira-Costa et al. 1999) correspond to the already published model. The observed flattening of the spectrum and its turnover around 20 GHz agree well with the spinning dust predictions.

Microwave emission from spinning grains is expected to be polarized if grains are aligned. Alignment of ultrasmall grains which are essentially large molecules is likely to be different from alignment of large (i.e. $a > 10^{-6}$ cm) grains. One of the mechanisms that might produce alignment of the ultrasmall grains is the paramagnetic dissipation mechanism by Davis and Greenstein (1951). The Davis-Greenstein alignment mechanism is straightforward: for a spinning grain the component of interstellar magnetic field perpendicular to the grain angular velocity varies in grain coordinates, resulting in time-dependent magnetization, associated energy dissipation, and a torque acting on the grain. As a result grains tend to rotate with angular momenta parallel to the interstellar magnetic field.

Lazarian & Draine (2000, henceforth LD00) found that the traditional picture of paramagnetic relaxation is incomplete, since it disregards the so-called "Barnett magnetization" (Landau & Lifshitz 1960). The Barnett effect, the inverse of the Einstein-De Haas effect, consists of the spontaneous magnetization of a paramagnetic body rotating in field-free space. This effect can be understood in terms of the lattice sharing part of its angular momentum with the spin system. Therefore the implicit assumption in Davis & Greenstein (1951)– that the magnetization within a *rotating grain* in a *static* magnetic field is equivalent to the magnetization within a *stationary grain* in a *rotating* magnetic field – is clearly not exact.

LD00 accounted for the "Barnett magnetization" and termed the effect of enhanced relaxation arising from grain magnetization "resonance relaxation". It is clear from Fig. 1 that resonance relaxation persists at the frequencies when the Davis-Greenstein relaxation vanishes. However the polarization is marginal for $\nu > 35$ GHz anyhow. The discontinuity at $\sim 20$ GHz is due to the assumption that smaller grains are planar, and larger grains are spherical. The microwave emission will be polarized in the plane perpendicular to magnetic field.

Can we check the alignment of ultrasmall grains via infrared polarimetry? The answer to this question is "probably not". Indeed, as discussed earlier, infrared emission from ultrasmall grains, e.g. 12 $\mu$m emission, takes place as grains absorb UV photons. These photons raise grain temperature, randomizing grain axes in relation to its angular momentum (see Lazarian & Roberge 1997). Taking values for Barnett relaxation from Lazarian & Draine (1999), we get the randomization time of the $10^{-7}$ cm grain to be $2 \times 10^{-6}$ s, which is less than grain cooling time. As the result, the emanating infrared radiation will be polarized very marginally. If, however, Barnett relaxation is suppressed, the randomization time is determined by inelastic relaxation (Lazarian & Efroimsky 1999) and is $\sim 0.1$ s, which would entail a partial polarization of infrared emission.

## POLARIZED EMISSION FROM MAGNETIC GRAINS

While the spinning grain hypothesis got recognition in the community, the magnetic dipole emission model suggested by Draine & Lazarian (1999, henceforth DL99) was left essentially unnoticed. This is unfortunate, as magnetic dipole emission provides a possible alternative explanation to the Foreground X. Magnetic dipole emission is negligible at optical and infrared frequencies. However, when the frequency of the oscillating magnetic field approaches the precession frequency of electron spin in the field of its neighbors, i.e. 10 GHz, the magneto dipole emissivity becomes substantial.

How likely is that grains are strongly magnetic? Iron is the fifth most abundant element by mass and it is well known that it resides in dust grains (see Savage & Sembach 1996). If 30% of grain mass is carbonaceous, Fe and Ni contribute approximately 30% of the remaining grain mass. Magnetic inclusions are widely discussed in grain alignment literature (Jones & Spitzer 1967, Mathis 1986, Martin 1995, Goodman & Whittet 1996). If a substantial part of this material is ferromagnetic or ferrimagnetic, the magneto-dipole emission can be comparable to that of spinning grains. Indeed, calculations in DL99 showed that less than 5% of interstellar Fe in the form of metallic grains or inclusions is necessary to account for the Foreground X at 90 GHz, while magnetite, i.e. $Fe_3O_4$, can account for a

[4] The very idea of grain rotational emission was first discussed by Erickson (1957). More recently, after the discovery of the population of ultrasmall grains, Ferrara & Dettmar (1994) noted that the rotational emission from such grains may be observable, but their treatment assumed Brownian thermal rotation of grains, which is incorrect.

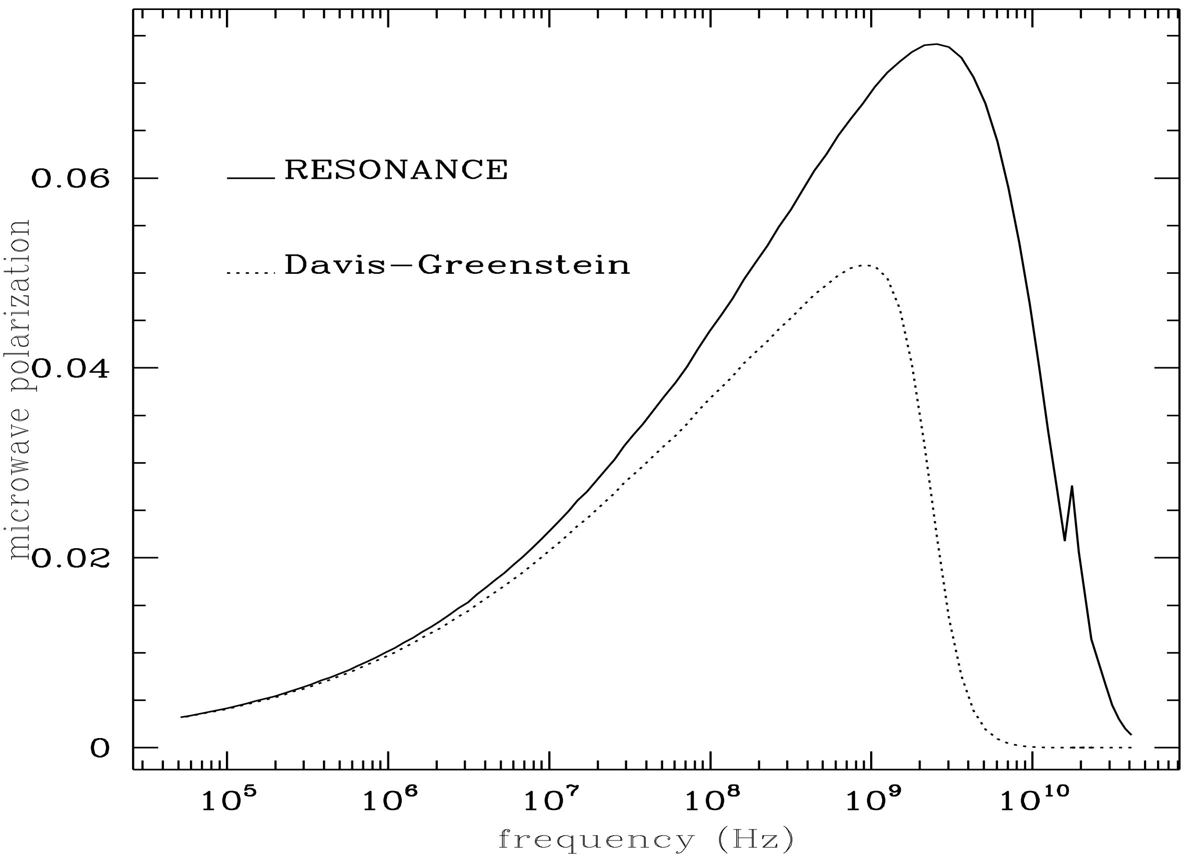


**FIGURE 1.** Polarization for both resonance relaxation and Davis-Greenstein relaxation for grains in the cold interstellar medium as a function of frequency (from LD00). For resonance relaxation the saturation effects (see eq. (1)) are neglected, which means that the upper curves correspond to the *maximal* values allowed by the paramagnetic mechanism.

considerable part of the anomalous emissivity over the whole range of frequencies from 10 to 90 GHz. Adjusting the magnetic response of the material, i.e. making it more strongly magnetic than magnetite, but less magnetic than pure metallic Fe, it is possible to get a good fit for the Foreground X (DL99).

How can magneto-dipole emission be distinguished from that from spinning grains? The most straightforward way is to study microwave emission from regions of different density. The population of small grains is depleted in dark clouds (Leger and Puget 1984) and this should result in a decrease of contribution from spinning grains. Private communication from Dick Crutcher who attempted such measurements corresponds to this tendency, but the very detection of microwave emissivity is a $3\sigma$ result. Obviously the corresponding measurements are highly desirable. As for now, magnetic grains remain a strong candidate process for producing part or even all of Foreground X. In any case, even if magnetic grains provide subdominant contribution, this can be important for particular cases of CMB and interstellar studies. For instance, polarization from magnetic grains may dominate that from spinning grains even if the emission from spinning grains is more of higher level.

The mechanisms of producing polarized magneto-dipole emission is similar to that producing polarization of electro-dipole thermal emission emitted from aligned non-spherical grains (see Hildebrand 1988). There are two significant differences, however. First, strongly magnetic grains can contain just a single magnetic domain. Further magnetization along the axis of this domain is not possible and therefore the magnetic permeability of the grains gets anisotropic: $\mu = 1$ along the domain axis, and $\mu = \mu_{\perp}$ for a perpendicular direction. Second, even if a grain contains tiny magnetic inclusions and can be characterized by isotropic permeability, polarization that it produces is orthogonal to the electro-dipole radiation emanating through electro-dipole vibrational emission. In case of the electo-dipole emission, the longer grain axis defines the vector of the electric field, while it defines the vector of the magnetic field

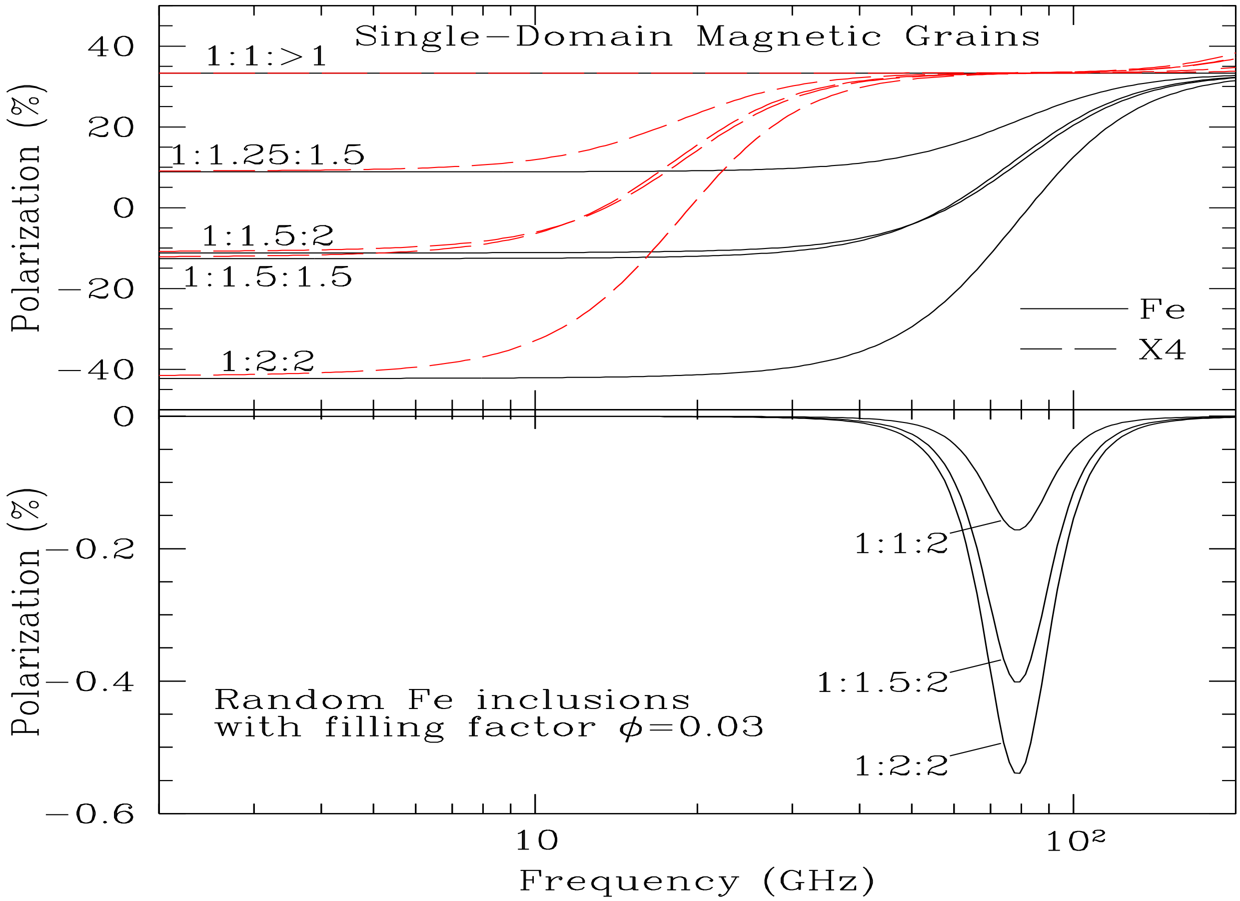


**FIGURE 2.** Polarization from magnetic grains (from DL99). Upper panel: Polarization of thermal emission from perfectly aligned single domain grains of metallic Fe (solid lines) or hypothetical magnetic material that can account for the Foreground X (broken lines). Lower panel: Polarization from perfectly aligned grains with Fe inclusions (filling factor is 0.03). Grains are ellipsoidal and the result are shown for various axial ratios.

in case of magneto-dipole emission.

The results of calculations for single domain iron particle (longer axis coincides with the domain axis) and a grain with metallic Fe inclusions are shown in Fig. 2. Grains are approximated by ellipsoids $a_1 < a_2 < a_3$ with $\mathbf{a_1}$ perfectly aligned parallel to the interstellar magnetic field **B**. The polarization is taken to be positive when the electric vector of emitted radiation is perpendicular to **B**; the latter is the case for electro-dipole radiation of aligned grains. This is also true (see Fig. 3) for high frequency radiation from single dipole grains. It is easy to see why this happens. For high frequencies $|\mu_\perp - 1|^2 \ll 1$ and grain shape factors are unimportant. The only important thing is that the magnetic fluctuations happen perpendicular to $\mathbf{a_1}$. With $\mathbf{a_1}$ parallel to **B**, the electric fluctuations tend to be perpendicular to **B** which explains the polarization of single domain grain being positive. For lower frequencies magnetic fluctuations tend to happen parallel to the intermediate size axis $\mathbf{a_2}$. As the grain rotates about $\mathbf{a_1} \| \mathbf{B}$, the intensity in a given direction reaches maximum when an observer sees the $\mathbf{a_1}\mathbf{a_2}$ grain cross section. Applying earlier arguments it is easy to see that magnetic fluctuations are parallel to $\mathbf{a_2}$ and therefore for sufficiently large $a_2/a_1$ ratio the polarization is negative. *The variation of the polarization direction with frequency presents the characteristic signature of magneto-dipole emission from aligned single-dipole grains and it can be used to separate this component from the CMB signal*. Note that the degree of polarization is large, and such grains may substantially interfere with the attempts of CMB polarimetry. Even if the intensity of magneto-dipole emission is subdominant to that from rotating grains, it can still be quite important in terms of polarization. A relatively weak polarization response is expected for grains with magnetic inclusions (see Fig. 2). The resulting emission is negative as magnetic fluctuations are stronger along longer grain axes, while the short axis is aligned with **B**.

Systematic studies of dust foreground polarization should improve our insight into the formation dust, its structure, its composition. For instance, DL99 showed that the present-day microwave measurements do not allow more than 5% of Fe to be in the form of metallic iron. More laboratory measurements of microwave properties of candidate materials are also necessary. Some materials, e.g. iron, were studied at microwave range only in the 50's and this sort of data must be checked again using modern equipment.

## POLARIZED DUST EMISSION AS A FOREGROUND TO CMB MEASUREMENTS

As we have seen in the previous sections, dust emission at microwave and submillimeter frequencies is likely to be polarized, thus representing a foreground emission to the cosmic microwave background polarized (hereafter CMBP) emission. In order to estimate the impact of this foreground on the CMBP measurements, it is essential to compare not only their relative dominance in different frequency channels, but also their spatial statistical distribution since the CMBP emission is expected to have a very distinctive spatial distribution. It is therefore important to compare foreground and background emission at different wavelengths and *at different scales*. In the following we will concentrate on frequencies where the thermal emission of dust is dominant over the rotational (or magnetic dipole) emission. This corresponds in particular to the frequency range covered by the High Frequency Instrument aboard the Planck satellite, which offers the highest possible sensitivity to the tiny CMBP emission.

### Depolarization factors

Given the low optical depth of the diffuse ISM (where the CMBP measurements will be made, i.e. at high Galactic latitude), the polarized emission of dust for a particular line of sight depends on the integrated signal throughout the entire emitting medium. Even if the grains are perfectly aligned with their short axis along the magnetic field lines, the magnetic field lines reversals will act as a depolarization mechanism on the observed dust emission. The statistical distribution of the polarized emission is therefore the result of a complicated interplay between the dust density distribution, possibly its temperature distribution (resulting in varying alignment efficiencies, as previously discussed), and the magnetic field distribution (direction and amplitude a priori). Following Greenberg(1968), we will define a depolarization factor $\Phi$ which gives the relation between the intrinsic dichroic polarised cross-section of a grain and the (average) observed polarized cross-section along a typical line of sight. This factor is defined as follows:

$$\Phi = RF\cos\gamma \tag{1}$$

$$R = \frac{3}{2}(\langle\cos^2\beta\rangle - \frac{1}{3}) \tag{2}$$

$$F = \frac{3}{2}(\langle\cos^2\theta\rangle - \frac{1}{3}) \tag{3}$$

where $\beta$ and $\theta$ are the angle between the grain major axis (axis of maximal inertia) and the direction of the magnetic field, and the angle between the random (turbulent) component of the magnetic field and the regular component respectively; finally $\gamma$ is the angle between the regular component of the magnetic field with the plane of the sky. In principle the Rayleigh reduction factor $R$ is decomposed into the partial alignment of the grain angular momentum $\mathbf{J}$ with its major inertia axis and the partial alignment of $\mathbf{J}$ with the magnetic field. However the statistical distributions of these two angles are generally not independent (see for instance Roberge & Lazarian 1999) and it is precisely the determination of their combined statistical average $R$ that is the goal of grain alignment theory. In this section, we will assume a "worst case scenario" (in terms of CMBP measurement contamination) by assuming that the grain alignment mechanism is perfect (hence $R = 1$). We are then left with the depolarization due to magnetic field line warping, and the value of the polarized cross-section which depends on grain composition, size and axis ratio (we assume grains of spheroidal shape, see e.g. Lee & Draine 1985).

### Polarized cross-sections

The polarized cross-sections in the infrared wavelengths are primarily a function of the grain composition and shape, and are not very sensitive to the size distributions of the grains provided that the wavelengths considered are much

larger than the maximal grain sizes considered. In particular, the spectro-polarimetric properties of grains around absorption features of their component materials can be used to constrain the grain axis ratios in the assumption of spheroidal shapes (see e.g. Lee & Draine 1985, Hildebrand & Dragovan 1995). For instance, prolate and oblate spheroidal grains will have different locations of the peak polarization in absorption around the $9.7\mu m$ silicate feature. The $3.1\mu m$ ice feature can be used also to distinguish between prolate and oblate grains for a fixed grain core composition. Both Lee & Draine (1985) and Hildebrand & Dragovan (1995) find that oblate grains with axis ratios in the range 1:2 and 2:3 can reproduce the observations reasonably well. For the mixture of silicate and graphite grains needed to reproduce the $9.7\mu m$ and $2.2\mu m$ absorption features, and for a given grain shape one can compute the polarization efficiency in the millimeter range to be of order $\sim 35\%$ for a perfectly aligned grain in the plane of the sky (Hildebrand & Dragovan 1995). The difference between this theoretical upper limit of polarization efficiency and the observed histograms of polarization degree in emission at $100\mu m$ (peak at 2% and maximum around 9%) toward the Orion nebulae would then be explained by the depolarization factors described in the preceding section, i.e. the magnetic field lines entanglement and the partial alignment of grains. To estimate these factors in the diffuse ISM, we will follow a pragmatic approach described in Prunet et al. (1998).

## Estimating the polarization efficiency in emission: a first model

As explained in the beginning of this section, the estimation of the contamination of CMBP measurements by polarized dust emission requires not only the knowledge of the line of sight statistics of the polarization degree of dust emission, but also the spatial distribution of this emission. This in turn requires some knowledge of the 3-dimensional distribution of the dust and magnetic field lines. Prunet et al. (1998) argued that the Galactic HI maps (with their velocity-space information), together with the observed strong correlation of HI gas and dust distribution for low column densities (Boulanger et al. 1996) could be used to estimate power spectra of polarized dust emission. It should be noted here that their method relies on very simplistic assumptions to relate the velocity-space structure of the HI gas to the 3d distribution of the gas, as well as simple extreme cases of cross-correlation of the magnetic field distribution with the underlying gas density; so that the inferred power spectra represent at best a guideline to the expected distribution of dust polarized emission. However, the different assumptions concerning the interplay between the magnetic lines orientations and the gas density structures are wide enough that this rough modelling should provide good upper and lower bounds on the slope/normalization of the polarized dust emission power spectra. In order to estimate a "worst case scenario" of CMBP measurement contamination, they assumed a perfect alignment of dust grains on magnetic field lines in the diffuse ISM, so that the problem becomes independent of the magnetic field amplitude, as well as the dust temperature. This is of course not expected to be true for realistic grain alignment mechanisms, be it paramagnetic relaxation of radiative torques. With these assumptions they considered three cases for the relation between magnetic field lines and gas density:

- magnetic field lines parallel to gas filaments, defined as least gradient directions in the HI distribution.
- magnetic field lines randomly distributed in the plane perpendicular to these directions. This could represent the case of helical field configurations.
- constant magnetic field lines orientation.

They applied their method to the HI Dwingaloo survey at intermediate Galactic latitude to compute an average contamination for all-sky CMBP measurements. The first statistics that they derived is the histogram of the polarization degree in emission for the three different assumptions above, shown in figure 3. They used the same method to predict the polarized (spatial) power spectra of dust emission, more specifically the power spectra of the *electric* (E) and *magnetic* (B) modes of polarization, in order to compare them to the theoretical predictions for the CMBP emission (see figure 4). The power spectra for the electric and magnetic modes of polarized dust emission were computed in the flat sky approximation (Seljak 1996) from the Fourier coefficients of the Stokes parameters Q and U maps. They were then fitted by power laws, together with the temperature-polarization cross-correlation spectrum. This decomposition in electric and magnetic modes of polarization is of particular importance for the CMBP emission since scalar primordial perturbations of the metric can only produce electric modes of polarization in the CMBP, thus defining the magnetic modes as a tracer of the primordial tensor (gravitational waves) perturbations (see Seljak & Zaldarriaga 1997, Kamionkowski et al. 1997). The figures show the expected level of contamination by dust polarized emission for the two polarized channels of the Planck High Frequency Instrument that are most sensitive to CMBP (143 and 217GHz). One can see that for a broad range of scales the measurement of electric modes of polarization

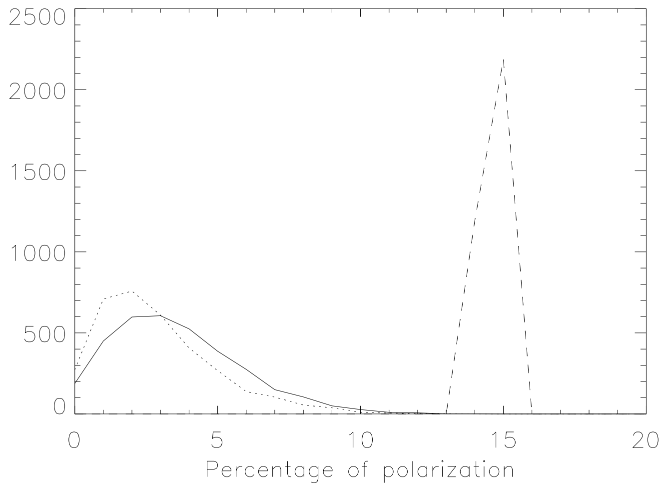


**FIGURE 3.** Predicted histograms of Galactic dust polarized degree in emission for the three different assumptions for magnetic field lines distribution (see text). The solid, dotted and dashed lines correspond respectively to the three cases described in the text. While two of the assumptions can reproduce the observations reasonably, the constant magnetic field case is clearly rejected.

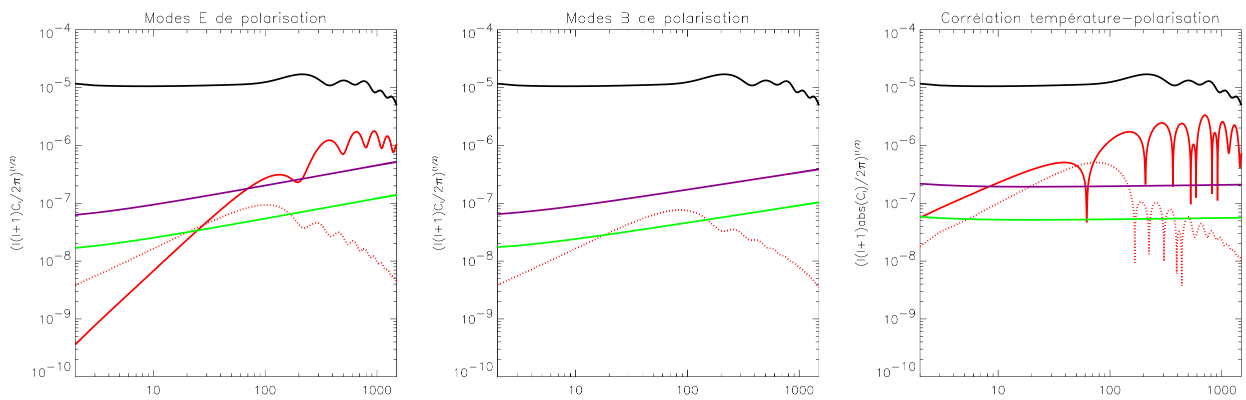


**FIGURE 4.** Predicted polarized $EE$, $TE$ and $BB$ power-spectra of Galactic dust, for two Planck HFI channels at 143 and 217 GHz, compared to the predicted spectra of the CMBP for a typical cosmological model. The green lines correspond to the 143 GHz dust spectra, and the purple ones to the same spectra at 217 GHz. The red lines show the different CMBP spectra for the chosen cosmological model, and the black line gives the level of the temperature $TT$ power spectrum for comparison.

in the CMBP should not be too much hindered by Galactic dust emission. This is even more true for the $TE$ cross-correlation. The B modes however (shown here for a typical cosmological model with $n_T = -0.1$ and $T/S = -7n_T$) are seriously contaminated by the dust emission, and our ability to measure them will rely heavily on our capacity of using the multi-frequency measurements of the polarized diffuse emissions in the millimeter and sub-millimeter wavelengths to disentangle the cosmological and Galactic signals (see e.g. Bouchet et al. 1999, Tegmark et al. 2000) using the fact that the intrinsic polarization degree in emission in the submillimeter should be roughly independent of wavelength.

This task could however be complicated by the expected complexity of the dust polarized emission (in particular the possible dependence of polarization efficiency with dust temperature, and more generally on the grains environment. It is therefore of prime importance for cosmology to better understand the polarized emission of Galactic dust and its behaviour, both spatially and spectrally.

## SUMMARY

The principal points discussed above are as follows:

- Dust provides the most intricate pattern of polarized radiation. The dependence of polarization of grain temperature, composition, size and environment makes the use of templates difficult.
- If anomalous emission in the range of 10-100 GHz is due to spinning dust particles, the polarization of the emission is marginal for frequencies larger than $\sim 35$ GHz. If the anomalous emission or part of it is due to magneto-dipole mechanism the polarization may be substantial and may exhibit reversals of direction with frequency.
- To get a better insight into the microwave properties of dust more laboratory studies are necessary. Some of them, e.g. measurements of the magnetic susceptibility of candidate materials at microwave frequencies, are trivial using the modern technology.
- Systematic studies of microwave polarization arising from dust will enable to determine the pattern of the CMB polarization and will shed light on many problems, including those of interstellar magnetic field and dust composition.

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